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Formation Location of Enceladus and Comets from D/H Measurements

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The building blocks of Enceladus could have formed in Saturn's subnebula, thus bearing no connection with planetesimals condensed in Saturn's feeding zone. We have shown that the D/H ratio in H_2O in Saturn's sub-nebula reaches the protosolar value in about 1,000 yr, well before ice forms again at Enceladus' location (several 10,000 yr). However, the D/H ratio measured by the Ion and Neutral Mass Spectrometer aboard the Cassini spacecraft in Saturn's satellite Enceladus is remarkably similar to the values observed in the nearly-isotropic comets. Hence the building blocks of Enceladus formed in the solar nebula. Nearly-isotropic comets originate from the Oort cloud. Delivery of material into the Oort cloud reservoir is controlled by Uranus-Neptune scattering. The D/H ratio in comets is therefore representative of that of the location of Uranus-Neptune at the time of formation of the Oort cloud. Since D/H strongly depends on heliocentric distance in the solar nebula, the similarity of D/H ratios links the primordial source region of the nearly-isotropic comets with the formation location of Enceladus. This precludes these comets from having formed beyond $\sim$15 AU from the Sun. which in turn implies that Uranus and Neptune were originally closer to Saturn's location during the feeding of the Oort cloud, likely in the 12-15 AU region. Such a configuration is consistent with the Nice model of evolution of the outer Solar System.

103P/Hartley 2 being D-poor compared to these bodies questions the current models. A fraction of ecliptic comets could have formed at closer distances from the Sun than assumed here and has been ejected outward and then display a low R/H ratio. However, they would only represent a small fraction of all ecliptic comets.

The high level of deuteration predicted in ecliptic comets from the description of the isotopic exchange between H2 and H_2O in the gas phase of the disk is based on classical models of the solar nebula (the alpha-turbulent model) in which the disk's temperature, pressure and density decrease monotonically with increasing heliocentric distance. These models do not consider the possible presence of sporadic and local phenomena such as shock waves that have been invoked to speed up the formation of planetesimals and trigger the crystallization of initially amorphous silicates prior to their incorporation in comets. Shock waves in the outer nebula could have locally increased the disk's temperature and pressure conditions and might have significantly decreased the deuteration level of the H_2O ice formed at this place. A possibly extended, both in time and space, major heating could have been induced by the inflow of the presolar cloud or envelop onto the outer part of the accretion disk at the time of the disk's formation. The influence of this mechanism on the outer disk's thermodynamic conditions and chemistry remains to be investigated.